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An Efficient Framework for Improving Microgrid Resilience against Islanding with Battery Swapping Stations

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ABSTRACT In this paper, an efficient bi-level framework is proposed to enhance the resilience of microgrids (MGs) against islanding due to low probability-high impact events by incorporating battery swapping stations (BSSs). In the emergency condition, MG solves the upper-level of the proposed model to report the desired energy transaction including surplus energy and unsupplied loads during the islanding period to the BSSs coordinator. The lower-level problem will be solved with an iterative algorithm by BSSs coordinator to report different plans of energy transactions and their prices to the MG during the emergency period. The price of each energy transaction plan is determined based on a bonus mechanism. Finally, MG will choose the best plan of energy trading considering a new proposed perspective of resilience improvement. Furthermore, a new formulation for BSS operation with fewer variables in comparison to the previous works is proposed in this paper. Simulations are carried out on an MG with two BSSs to verify the proposed model.

INDEX TERMS Battery swapping station, islanding, low probability-high impact events, microgrid, resilience.

NOMENCLATURE

Indices and sets

b, b', N_{bss}^{bat}	Indices and number of batteries in BSS *bss*
bss, N_{BSS}	Index and number of BSS
N_{bss}^{st}	Number of slot in BSS *bss*
t	Index of hour

Parameters

$N_{t,bss}^{sw}$	Number of EVs in the BSS *bss* for the swapping service in hour *t*
P_t^{PV} / P_t^{wind}	Output power of PV/wind turbine in hour *t*
P_t^{load}	Power demand of MG in hour *t*
$\overline{P}_{bss-MG}$	Maximum capacity of power exchange between BSS *bss* and MG
$\overline{P}^{MT} / \underline{P}^{MT}$	Maximum/minimum output power of micro-turbine
$\overline{P}^{ch,mg} / \overline{P}^{dch,mg}$	Maximum charging/discharging power of the battery in MG
$\overline{P}_b^{ch,bss} / \overline{P}_b^{dch,bss}$	Maximum charging/discharging power of battery *b* in BSS *bss*
$\overline{SoC}^{mg} / \underline{SoC}^{mg}$	Maximum/minimum state of charge of the battery in MG
$SoC_{bat}^{f} / SoC_{bat}^{e}$	Maximum/minimum state of charge of batteries in BSSs
t_0, T	Starting and ending hours of the emergency period
$VOLL_{mg}$	Value of MG lost load
ρ^{sw}	Battery swapping price
γ	A variable penalty factor that different plans of energy transactions can be obtained by it
$\eta^{ch,mg} / \eta^{dch,mg}$	Battery charging/discharging efficiency in MG
$\eta_b^{ch,bss} / \eta_b^{dch,bss}$	Battery *b* charging/discharging efficiency in BSS *bss*
λ_t^{mp}	Energy market price in hour *t*
ε	Convergence tolerance

Variables

P_t^{MT}	Output power of micro-turbine (MT) in hour t
P_t^{report}	Desired power transaction with BSSs in point of view of MG in hour t
P_t^{uns} / P_t^{sur}	Unsupplied load/surplus energy of MG in hour t that is reported to the BSSs coordinator
$P_t^{ch,mg}$ / $P_t^{dch,mg}$	Charging/discharging power of the battery in MG in hour t
$P_{t,bss}^{BSS-MG}$	Power exchange between BSS bss and MG in hour t
$P_{t,b}^{ch,bss}$ / $P_{t,b}^{dch,bss}$ / $P_{t,b}^{sw,bss}$	Charging/discharging/swapping power of battery b in hour t in BSS bss
SoC_t^{mg}	State of charge of the battery in MG in hour t
$SoC_{t,b}^{bss}$	State of charge of battery b in BSS bss in hour t
$v_t^{ch,mg}$ / $v_t^{dch,mg}$	A binary variable for determining charging/discharging of the battery in MG in hour t
$v_{t,b}^{ch,bss}$ / $v_{t,b}^{dch,bss}$ / $v_{t,b}^{sw,bss}$	A binary variable for determining charging/discharging/swapping of battery b in BSS bss in hour t
$\lambda_{t,bss}^{k}$	Price of trading power in hour t between MG and BSS bss in kth iteration of the lower-level problem

I. INTROUDUCTION

Low probability-high impact events (LPHIE), such as hurricanes, floods and earthquakes, disrupt the operation of critical infrastructures. The impact of power networks on the quality of life and health cannot be ignored and it is highlighted when dependencies of other infrastructures on the power network are considered [1]. The restoration of damaged power networks against LPHIE can take a long time (e.g., several weeks). Therefore, it is vital to have high resilient energy networks [2]. There are different strategies including operation-oriented and planning-oriented to improve resilience considering the natural disasters that threaten the power networks [3].

The planners of the power networks implement different strategies to enhance resilience considering the type of natural disaster and the type of the power network. Different solutions such as power poles or substation hardening are utilized in [4] and [5] to improve the resilience of a power distribution network and a transmission network against earthquakes and hurricanes, respectively. In [6], power generation planning for a microgrid is solved based on the resilience improvement concept. Automation as an efficient strategy is utilized in [7] to improve the resilience of power distribution networks. A linear optimization programming is proposed in [8] to enhance the resilience of power distribution networks against earthquakes with battery energy storage siting and sizing. Placement of distributed energy resources and power lines as other resilience improvement strategies are used in [9] to improve the resilience of microgrids based on N-k contingency.

The operators try to improve the resilience of power networks by identifying the potential of the network and equipment. Sectionalizing the main network after an LPHIE into smaller self-sustained networks named microgrids (MGs) can restore the disconnected loads [10]. To implement this strategy in the network, a microgrid formation model based on nonlinear programming is proposed in [11]. Reconfiguration of the networks reroutes energy with the aid of tie lines and increases the probability of disconnected loads restoration [12]. Dispatching of mobile power sources and repair crews in the distribution networks is studied in [13] and it is shown that the co-optimization method significantly improves the network restoration service. Demand response program which is proved in many works such as [14] as an efficient tool in the operation and planning of energy systems is also used in [15] to enhance the resilience of distribution systems.

MGs, due to their structure, are the most resilient power networks against LPHIEs [16]. An MG is defined by the U.S. Department of Energy (DoE) as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode”. A key feature in the resilience of an MG is the ability to isolated operation for a long time when an LPHIE occurs in the upstream network. MGs with islanded-operation capabilities can also provide energy for utility grids to enhance resilience in emergency conditions. In [17], it is studied that multi-energy microgrids have the capability to improve their resilience with proactive scheduling against predictable natural disasters such as hurricanes. In [18], an energy management system is designed for MGs to restore the disconnected loads of the distribution network. In [18], it is assumed that the distribution network owns the MGs. But, there should be a market for energy transactions if MGs do not belong to the utility grid. Regarding this condition, an interaction framework is proposed in [19] for privately-owned MGs to improve the resilience of the utility grid. In [19], each MG solves the energy management problem for the emergency period by changing the incentive price in an allowable interval and sends the bid-quantity energy block to the distribution network. The distribution network chooses the best plan for the restoration of the damaged network. Now, consider the situation that an MG suffers from energy shortage due to isolation after a disturbance in the utility grid which is an emergency condition for MG. The interaction of MG with other possible entities for delivering energy is vital in this condition. The main challenge is that if the entities are

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private, there should be a mechanism for motivating the entities to sell energy to the MG. These entities can be different. In many research works, this problem is studied when the network includes multiple MGs. An outage management system is proposed in [20] to enhance the resilience of multi MGs. In other words, in [20], the distribution system operator manages the deficit/surplus energy of MGs to support each other in emergency conditions. A market mechanism with the management of the distribution system operator is proposed in [21] for multi-MGs to quantify the value of emergency transaction energy. In [21], each MG schedules the resources and generates bids at the first stage. In the second stage, the distribution system operator runs the emergency market in order to calculate the price and energy transactions. A peer-to-peer energy transaction framework is proposed in [22] to improve the resilience of networked MGs. This framework needs a lot of data exchange in emergency conditions when the cyber links are vulnerable and it is suggested that the dependency of the framework on the cyber links be minimized, especially in an emergency condition.

Electrical vehicles (EVs) have been increasingly penetrated in our life. As mentioned in [23], there are two challenges with plug-in EVs charging management. Firstly, the EV owners intend to spend the minimum time for charging the empty batteries. Secondly, it is difficult to manage the stochastic behavior of EV owners to charge the empty batteries based on the interest of power distribution networks. An incentive policy for EV owners is proposed in [24] to manage the battery charging and the parking lots are placed based on such policy. A battery swapping station (BSS) is the other strategy for charging the EVs. The empty batteries of EVs can be replaced in a short time. Furthermore, BSSs can easily manage the batteries charging in order to help the operation of power distribution networks. BSSs are implemented in [25] and [26] to improve the frequency regulation and peak shaving of the distribution network, respectively.

This paper focuses on the resilience improvement of an MG by using the potential of BSSs. The interaction of BSS and MG in normal conditions is investigated in [27-29]. In [27], alternative direction method of multipliers (ADMM) with restart algorithm is used to schedules the operation of an MG and BSS based on a pre-determined price of energy during a day. ADMM algorithm exchanges data regularly between MG and BSS to be converged. A bi-level problem is designed in [28] to coordinate the interaction of a BSS and an isolated MG. To determine the price of transaction energy in [28], a real time-pricing mechanism is utilized and the problem is solved by a hybrid algorithm which is called JAYA-BBA. The mentioned algorithm solves the problem through alternate iterations between the two levels. Two approaches, including a peer-to-peer method and a leader-follower method, are proposed in [29] to coordinate the scheduling of an MG and a BSS. As it is mentioned earlier, peer-to-peer methods are designed based on the continuous communicating of two entities that are appropriate in normal conditions. In the leader-follower method, all the information about BSS and MG operating conditions is needed for solving the problem.

In light of the reviewed literature, it can be clearly observed that although some works study the interaction of an MG and BSSs, there are still important issues which have been left unclear in this field, especially in emergency condition: 1- There is no framework for energy transaction in emergency conditions in previous works, 2- Most of the works rely on continued data exchange to solve the problem which is not appropriate in the emergency conditions.

Briefly, the major contributions of this paper are highlighted as follows:

- An efficient framework is proposed to enhance the resilience of MGs against islanding with BSSs.
- A new perspective of resilience improvement is introduced. It is shown resilience improvement cannot be determined only by the value of lost loads (VOLL) and different parameters such as social resilience and the behavior of loads can affect it.
- The proposed framework does not require frequent exchanging data between MG and the BSSs coordinator. In other words, the cyber link of MG-BSSs coordinator only used once and twice by the BSSs coordinator and MG, respectively.
- A new formulation with fewer variables in comparison with the previous works such as [27-30] is proposed for BSS operation.

The remainder of this paper is organized as follows. The proposed model framework is investigated in section II. A new perspective of resilience improvement is introduced in section III. Section IV presents the problem formulation and solution methodology. Numerical results are presented and analyzed in section V and finally, section VI concludes the paper.

II. THE PROPOSED MODEL FRAMEWORK

When Fig. 1 shows systems where an MG and two privately-owned BSSs could interact. MG has different power generation sources including PV, wind turbine (WT) and a micro-turbine. MG can import/export energy from/to BSSs and the utility grid. Furthermore, MG depends on the utility grid as the main source during a normal operation in a day.

Imagine, an emergency condition for MG is triggered and followed by an islanding event due to an LPHIE occurrence in the utility grid (upstream network). In this situation, MG should import energy from neighboring entities, which are assumed to be BSSs in this paper. The proposed model in the emergency condition follows the below steps to improve the resilience of MG.

1- MG solves the upper-level of the proposed model and reports the desired energy transaction including surplus

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energy and unsupplied loads during the emergency period to the BSSs coordinator. MG operator sends the information to the BSSs coordinator through the cyber link of MG-BSSs coordinator.

2- BSSs coordinator solves the lower-level of the proposed model to report different plans of energy transactions and their prices based on a bonus mechanism to MG. The bonus mechanism is designed in such a way that MG intends to sell surplus energy with the market price to the BSSs and to purchase energy for preventing load shedding with market price and a variable bonus. However, the final price of purchasing energy is less than the value of lost loads.

3- MG investigates all the plans of energy transactions and chooses the best one considering a new perspective of resilience improvement.

It should be noticed this framework protects the privacy of MG.

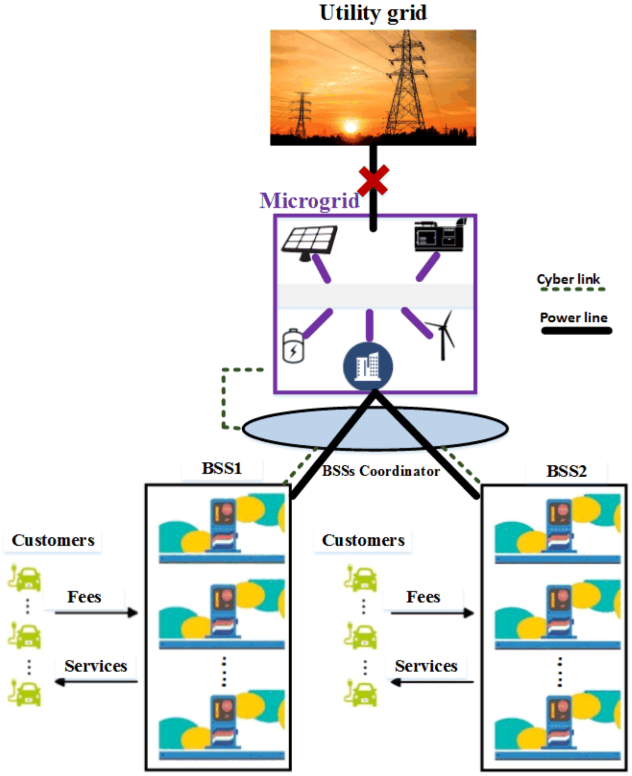

FIGURE 1. The interaction of MG-BSSs in emergency condition.

III. NEW PRESPECTIVE OF RESILIENCE IMPROVEMENT

In resilience improvement studies, high-impact events are mainly considered whose impact will last longer and the system restoration process takes more time compared to normal faults. Therefore, many other indices such as the behavior of loads and social resilience will affect the resilience improvement concept. As an example, imagine, an MG as a power network will experience islanding for a long time due to an LPHIE occurrence in the utility grid. To help better understanding the concept, let's assume a shorter islanding duration (e.g., three hours). According to Fig. 2-A and an equal VOLL at all hours, MG must perform load shedding in the emergency period as amounts of 20, 40 and 60 kW in hours *t1*, *t2* and *t3*, respectively, to keep supply-demand balance. Now imagine other entities that are linked to MG such as a BSS can export 60 kWh energy to MG during an emergency condition. Such action can be realized, for example, in any of the forms depicted in Fig. 2-B to Fig.2-D. The main question is in which of the mentioned form(s), the resilience of MG will be more improved? It should be noticed in the point of view of VOLL, all the forms are similar.

If an MG feeds some residential loads with low social resilience (patience of people against power outage), MG will intend that each load only experiences a maximum one-hour power outage to avoid social dissatisfaction. Therefore, Fig. 2-B is the best solution for the resilience enhancement of MG. As can be seen, MG cannot decide to improve the resilience only based on the VOLL in this condition.

Now imagine the situation that MG loads are commercial and the electricity is important for them at night (hour t3 is considered at night and the others in the day). So, MG prefers to restore the loads with another plan as shown in Fig. 2-C. Finally, the last plan which is shown in Fig. 2. D is the best solution for resilience enhancement when MG desires to supply a pre-determined number of loads during the emergency period.

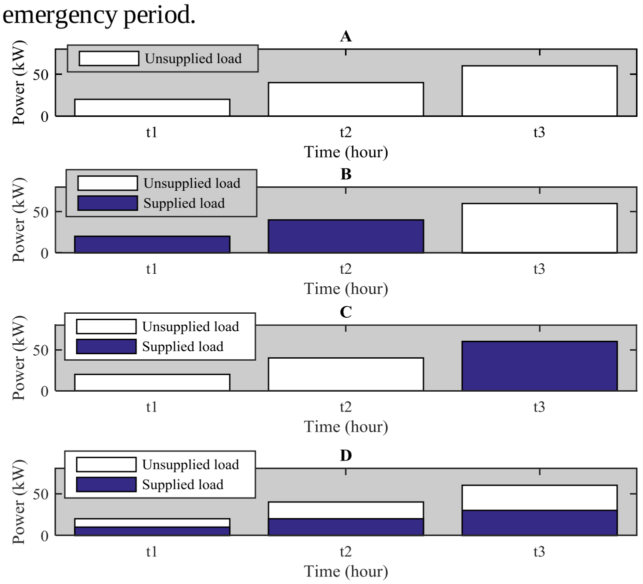

FIGURE 2. Different plans for load restoration of MG during emergency period.

IV. PROBLEM FORMULATION AND SOLUTION METHODOLOGY

The bi-level model is presented in this section. The bi-level model aims to enhance the resilience of MG against islanding with an appropriate interaction with BSSs. Therefore, the model will be run upon the isolation of MG due to an LPHIE occurrence in the utility grid and it will be continued until the termination of isolation.

A. UPPER-LEVEL: MG SCHEDULING IN EMERGENCY PERIOD

The objective function of this level is formulated to minimize the cost of unsupplied loads during the emergency period considering VOLL:

$$OF_{MG} = Min\sum_{t=t_0}^{t_0+T} P_t^{uns} VOLL_{mg} \tag{1}$$

A set of technical constraints must be satisfied during the operation of MG.

- Power balance of MG:

According to (2), MG operator reports $P_t^{report} = [P_t^{uns}, -P_t^{sur}]$ during the emergency period to the BSSs coordinator after solving the upper-level problem. It should be noticed P_t^{report} includes desired purchasing energy (to avoid load shedding during the emergency condition) and selling surplus energy in the point of view of MG. If P_t^{report} is positive ($P_t^{uns} > 0, P_t^{sur} = 0$), it means MG intends to purchase power from BSSs. Otherwise ($P_t^{uns} = 0, P_t^{sur} > 0$), MG intends to sell energy to BSSs.

$$\begin{aligned} &P_t^{PV} + P_t^{MT} + P_t^{wind} + P_t^{uns} + P_t^{dch,mg} = \\ &P_t^{load} + P_t^{ch,mg} + P_t^{sur} \end{aligned} \tag{2}$$

- Operation limit of MT:

$$\underline{P}^{MT} \le P_t^{MT} \le \overline{P}^{MT} \tag{3}$$

- Unsupplied load:

$$P_t^{uns} \le P_l^{load} \tag{4}$$

- Battery operation:

$$0 \le P_t^{ch,mg} \le \overline{P}^{ch,mg} v_t^{ch,mg} \tag{5}$$

$$0 \le P_t^{dch,mg} \le \overline{P}^{dch,mg} v_t^{dch,mg} \tag{6}$$

$$SoC_t^{mg} = SoC_{t-1}^{mg} + \eta^{ch,mg} P_t^{ch,mg} - \frac{P_t^{dch,mg}}{\eta^{dch,mg}} \tag{7}$$

$$\underline{SoC}^{mg} \le SoC_t^{mg} \le \overline{SoC}^{mg} \tag{8}$$

$$v_t^{ch,mg} + v_t^{dch,mg} \le 1 \tag{9}$$

B. LOWER-LEVEL: BSSS COORDINATOR DECISION MAKING

At this level, the BSSs coordinator aims to determine different plans of energy transactions and their price. The lower-level problem is formulated as:

$$OF_{BSSs} = Min\sum_{t=t_0}^{t_0+T}\left[\begin{aligned}&\sum_{bss=1}^{N_{BSS}}\left(\begin{aligned}&-\lambda_{t,bss}P_{t,bss}^{BSS-MG} - \\ &\rho^{sw}(SoC_{bat}^{f} - Soc_{bat}^{e})N_{t,bss}^{sw}\end{aligned}\right) \\ &+\gamma\left(P_t^{report} - \sum_{bss=1}^{N_{bss}} P_{t,bss}^{BSS-MG}\right)^2\end{aligned}\right] \tag{10}$$

The objective function includes three terms. The first term is the cost related to energy transactions with MG. As it is mentioned earlier, one goal of the designed framework is to determine the prices of energy transactions in the emergency condition which is visible in the first term. Based on the designed bonus mechanism that will be explained later, the price in each hour of each energy transaction plan is the sum of market price and a variable bonus. The maximum bonus can be obtained if BSSs can provide the reported needed power demand to prevent load shedding in MG. The second term indicates the swapping cost gained from EV owners of each BSS. The third term tries to minimize the difference of energy transactions from the MG and BSSs coordinators' viewpoint considering γ. In other words, γ is a variable penalty factor that generates different plans of energy transactions considering the reported desired energy transaction by MG as a reference. Consider Fig. 2 as an example, when γ is zero, BSSs intend to offer an energy transaction plan in form of Fig. 2-B to maximize the bonuses and finally the profit. But, when γ is large enough, Fig. 2-D will be offered as the energy transaction plan due to the impact of the third term of the objective function. Although, by changing γ, the profit of BSSs in different plans of energy transactions can be reduced. But, BSSs agree to trades energy with any plan of energy transactions with MG in emergency condition due to they can gain more profit with any amount of γ (any energy transaction plan) in comparison to the normal condition. In other words, the designed price mechanism in emergency conditions motivates BSS to trade energy with MG. The proposed framework is designed based on the honest behavior of MG and BSSs.

In the new formulation of the BSSs operation, three binary variables including $v_{t,b}^{ch,bss}$, $v_{t,b}^{dch,bss}$ and $v_{t,b}^{sw,bss}$ are defined for each battery of each BSS that show charging, discharging and swapping states. In each hour, only one of these binary variables can be 1. When $v_{t,bss,b}^{sw}$ in an hour is 1, it means that the battery must be swapped due to an EV request. In other words, the full battery will be changed by an empty battery. In this situation, *SoC* of battery *b* will drop from SoC_{bat}^{f} to SoC_{bat}^{e} . Based on this concept, a set of technical constraints must be satisfied during the operation of BSSs.

- Batteries operation constraints:

Constraints (11)-(13) show the allowable charging, discharging and swapping power of each battery in each hour, respectively. Equation (14) shows the state of charge of each battery in each hour. Constraint (15) limits the state of charge of each battery in an allowable range. As mentioned earlier, constraints (16)-(18) enforce that each battery in each hour can be operated only in one mode, i.e., charging, discharging or swapping. Constraint (19) expresses that the number of swapped batteries in each BSS in each hour must be equal to the EVs swap demand.

$$0 \le P_{t,b}^{ch,bss} \le \overline{P}_b^{ch,bss} v_{t,b}^{ch,bss} \tag{11}$$

$$0 \le P_{t,b}^{dch,bss} \le \overline{P}_b^{dch,bss} v_{t,b}^{dch,bss} \tag{12}$$

$$P_{t,b}^{sw,bss} = (SoC_{bat}^{f} - SoC_{bat}^{e}) v_{t,b}^{sw,bss} \tag{13}$$

$$SoC_{t,b}^{bss} = SoC_{t-1,b}^{bss} + \eta_b^{ch,bss} P_{t,b}^{ch,bss} - \frac{P_{t,b}^{dch,bss}}{\eta_b^{dch,bss}} - P_{t,b}^{sw,bss} \tag{14}$$

$$SoC_{bat}^{e} \le SoC_{t,b}^{bss} \le SoC_{bat}^{f} \tag{15}$$

$$v_{t,b}^{ch,bss} + v_{t,b}^{sw,bss} \le 1 \tag{16}$$

$$v_{t,b}^{dch,bss} + v_{t,b}^{sw,bss} \le 1 \tag{17}$$

$$v_{t,b}^{dch,bss} + v_{t,b}^{ch,bss} \le 1 \tag{18}$$

$$\sum_{b=1}^{N_{bss}^{bat}} v_{t,b}^{sw,bss} = N_{t,bss}^{sw} \tag{19}$$

- Slots operation:

It should be noticed, a number of slots are defined for each BSS. Constraint (20) expresses that the total number of batteries that can be charged/discharged in each hour is equal to available slots in each BSS. Furthermore, according to the constraint (21), all the slots of each BSS must have one mode in each hour. In other words, the BSS cannot import/export energy simultaneously from/to the MG.

$$\sum_{b=1}^{N_{bss}^{bat}} \left(v_{t,b}^{ch,bss} + v_{t,b}^{dch,bss} \right) \le N_{bss}^{st} \tag{20}$$

$$v_{t,b}^{ch,bss} + v_{t,b'}^{dch,bss} \le 1, \forall b, b' \in \left\{1, 2, ..., N_{bss}^{bat}\right\} \tag{21}$$

- BSS operation:

Power trading between each BSS and MG in each hour is obtained by (22). Equation (23) expresses that the power trading between each BSS and MG in each hour is in a limited range.

$$p_{t,bss}^{BSS-MG} = \sum_{b=1}^{N_{bss}^{bat}} P_{t,b}^{dch,bss} - \sum_{b=1}^{N_{bss}^{bat}} P_{t,b}^{ch,bss} \tag{22}$$

$$-\overline{P}_{bss-MG} \le p_{t,bss}^{BSS-MG} \le \overline{P}_{bss-MG} \tag{23}$$

- Energy trading constraints during the emergency condition:

Constraints (24)-(25) limit the energy trading between MG and BSSs considering the reported desired energy transaction by MG.

$$-p_t^{sur} \le p_{t,bss}^{BSS-MG} \le p_t^{uns} \tag{24}$$

$$-p_t^{sur} \le \sum_{bss=1}^{N_{BSS}} p_{t,bss}^{BSS-MG} \le p_t^{uns} \tag{25}$$

C. SOLOUTION METHODOLOGY

The upper-level problem denotes a mixed-integer linear programming (MILP) model and the lower-level one represents a mixed-integer quadratic programming (MIQP) model. Both models can be solved by the CPLEX solver in GAMS. In the solution, the upper-level of the problem is only solved for one time by the MG where the desired energy transaction (P_t^{report}) in the emergency period is reported to the BSS-coordinator.

The BSS coordinator solves the lower-level of the problem by changing γ to obtain different plans of energy transactions. In each iteration, the market price as the initial point is considered. To reach the solution at each iteration, an iterative algorithm is used to modify the price according to the following equation.

$$\lambda_{t,bss}^{k} = \begin{cases} \lambda_{t,bss}^{k-1} + \dfrac{P_{t,bss}^{BSS-MG}}{P_t^{uns}} \phi & \text{if } P_t^{uns} > 0 \\ \lambda_t^{mp} & \text{if } P_t^{sur} > 0 \end{cases} \tag{26}$$

In (26), ϕ is a constant bonus that each BSS can gain fully in an hour if it can provide the needed power demand of P_t^{uns} to prevent load shedding of MG. It should be noticed that ϕ is a contractual bonus between MG and the BSSs coordinator which is predetermined considering the emergency condition.

After modifying the price of energy, the BSS coordinator solves the lower-level of the problem again. This procedure will be continued until the stop criteria which is indicated in (27) is satisfied.

$$\sum_{bss=1}^{N_{BSS}} \sum_{t=t_0}^{T} \left| \lambda_{t,bss}^{k} - \lambda_{t,bss}^{k-1} \right| \le \varepsilon \tag{27}$$

After providing all plans of energy transactions by BSS coordinator, MG chooses the best one with the proposed new perspective of resilience improvement. Fig. 3 summarizes the proposed model and solution methodology.

D. UNCERTAINTIES AND THE PROPOSED MODEL

Although the mentioned formulation is deterministic, the proposed model is also efficient to handle the uncertain parameters including renewable energies output and load in the upper-level and the number of batteries to be swapped at each BSS in the lower-level of the problem.

In the upper-level of the model, the uncertain parameters can be handled using the methodology described in [19]. According to this methodology, the uncertain parameters can be modeled with appropriate probability distribution functions and after scenario generation, only a few scenarios will be chosen to be studied. The decision variables in this methodology include *here and now and wait and see*. Therefore, in the upper-level of the model, P^{uns}, P^{sur} which are reported to the BSS coordinator by microgrid are *here and now* variables and the others are *wait and see* variables.

In the lower-level of the model, the number of EVs that arrive in each hour at each BSS can be modeled with Poisson distribution which is used in [31].

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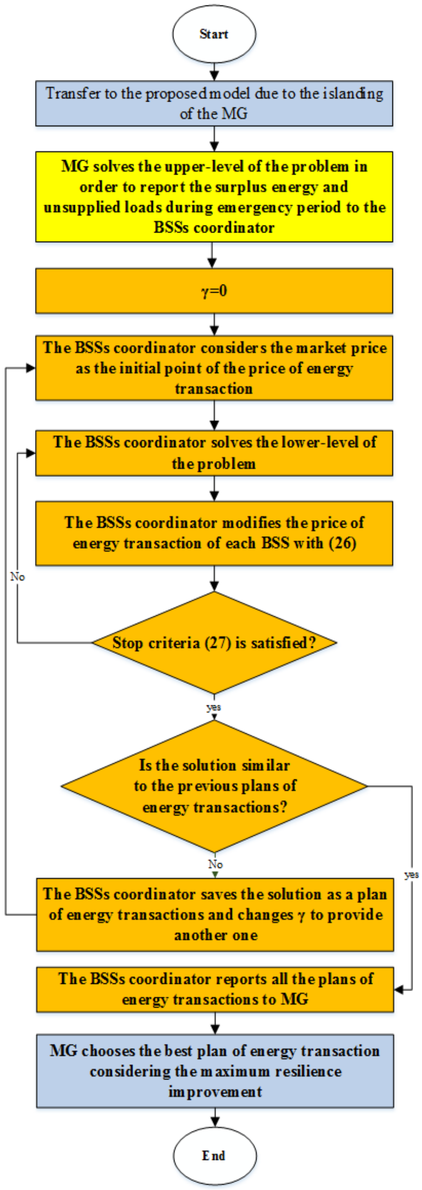

FIGURE 3. **Flowchart of the proposed model and solution methodology**

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, the case study is introduced and then the simulation results of the proposed model are discussed.

A. CASE STUDY

An MG (including a battery PV, WT and MT) with two BSSs are considered as the case study to show the effectiveness of the proposed model. The hourly load profile and the output of the renewable energies during the day when MG will be islanded are illustrated in Fig. 4. These sets of data are extracted from [31]. The minimum and maximum power output of MT in MG is 0 and 100 kW, respectively. The parameters of the battery in MG are shown in Table I which is extracted from [27].

It is assumed that there are two BSSs (BSS1 and BSS2) linked to MG with capacities 300 kW and 200 kW, respectively. The swap demands of EVs for both BSSs during the studied period are illustrated in Fig. 5. The swapped demand of EVs for BSS1 is extracted from [31]. The cost of battery swapping is considered as 1.4 $/kWh [31]. The number of slots for charging/discharging of the batteries in BSS1 and BSS2 is 8 and 5, respectively.

MG will be islanded due to an LPHIE occurrence at hour 1 and the islanding will be continued until hour 24. There are 40 and 30 batteries in BSS1 and BSS2, respectively. It is assumed 90% of batteries are full and the remaining ones are empty. $VOLL_{mg}$ is considered 7 $/kWh and MG decides to give a maximum 5 $ as a bonus in an hour if BSSs can cover all the unsupplied load of MG in that hour. Therefore, the maximum price of selling energy by BSSs to MG can be equal to 6 $/kWh (5 $/kWh as a maximum bonus and 1 $/kWh as the market price) that is lower than the value of lost loads of MG.

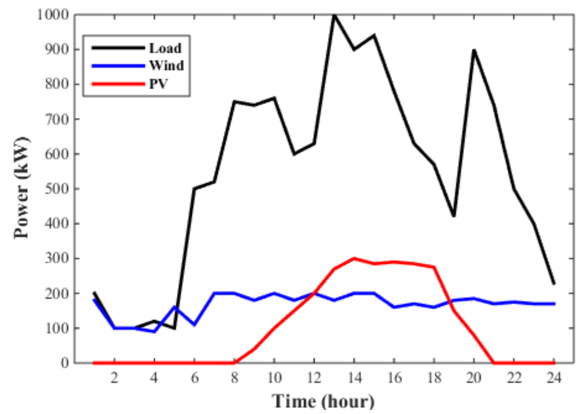

FIGURE 4. **Power generation of renewable sources and the load of MG.**

TABLE I
CHARACTERISTICS OF BATTERY IN THE MG UNDER STUDY

Capacity (kWh)	Maximum rate of charging/discharging power (kW)	Min-Max SoC (kWh)	Initial SoC	η_{ch} / η_{dch}
85	80-80	13-80	20%	0.92

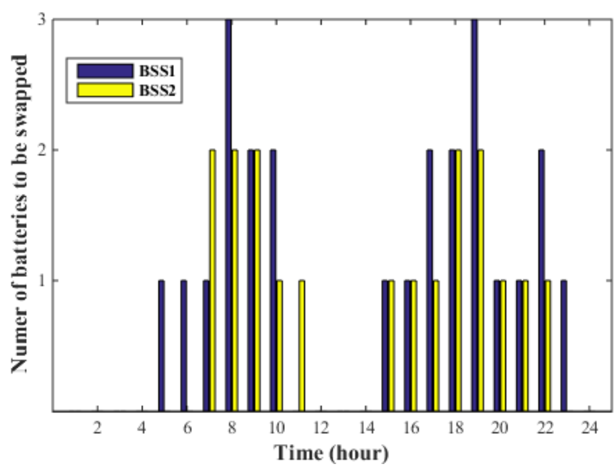

FIGURE 5. **The swap demands of EVs for both BSSs.**

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B. SIMULATION RESULTS

Case 1: In this case, the proposed framework is solved for the case study. Desired reported energy transactions by MG (upper-level of the problem) and different plans of energy transactions during emergency conditions (lower-level of the problem) are depicted in Fig. 6. According to Fig. 6 and (10), different plans of energy transactions can be obtained for a different amount of γ. When γ is small, BSSs intends to offer a plan in such a way that in each hour, the sold energy be closer to the unsupplied load in order to sell energy with higher prices. This is visible in the hours of 7, 15 and 23 of the energy transaction plan when γ is zero. But, for larger γ values, the plan of energy transaction tries to decrease the difference of load shedding of MG in the hours of emergency period.

According to Fig. 6 and the expected goal of the price mechanism, BSSs intends to charge the empty batteries by importing the surplus energy of MG and then sell it at a higher price to MG. As mentioned earlier, the price of sold energy by BSSs to MG based on the designed bonus mechanism is lower than $VOLL_{mg}$ and this procedure causes the resilience improvement of MG.

According to the plans of energy transactions in Fig. 6, each BSS intends to sell energy solely in an hour to gain all bonus of that hour. The energy trading prices of BSSs with MG for plan $\gamma = 1$ are illustrated in Fig. 7. It should be noticed the prices of each energy transaction plan can be calculated by (26). Furthermore, to show the efficiency of the iterative algorithm for solving the lower-level of the problem, the convergence of the algorithm in the plan of energy transaction when $\gamma = 1$ is tabulated in Fig. 8.

The profit of BSSs in different plans of energy transactions and also the profit of BSSs for energy trading with MG in normal conditions are given in Table II. It should be noticed that the price of energy in normal conditions is equal to the energy market price. Furthermore, constraints (24)-(25) are ignored in the normal conditions. According to Table 2, the profit of BSSs in any energy transactions plans is more than the profit of BSSs in normal conditions. Table 2 shows the efficiency of the designed bonus mechanism in motivating BSSs for energy trading with MG in the emergency condition. After receiving all the plans of energy transactions, MG must decide to choose the best one considering the maximum resilience improvement. From the MG operator's viewpoint of cost objective function in (1), all plans of energy transactions could be valid and acceptable. However, the ultimate choice will depend on satisfying other criteria as explained in Section III. If MG intends to decrease the frequency of loads inaccessibility to power, the plan of energy transaction when $\gamma = 0$ should be chosen. Although, with this choice, MG will face a large amount of load shedding in some hours. But, if MG intends to have load shedding in different hours of emergency period approximately close to each other, it should choose the plans of energy transactions when γ is 0.1 or 1.

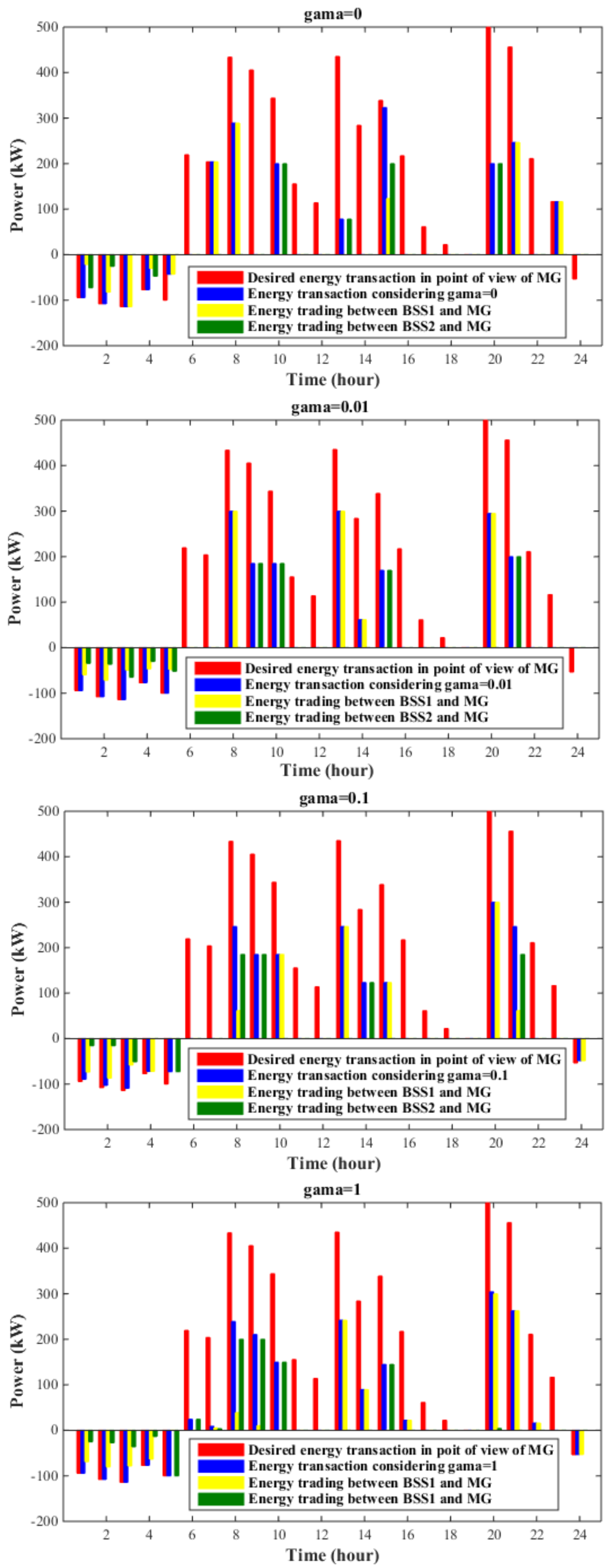

FIGURE 6. Different plans of energy transactions offered by BSSs coordinator to MG.

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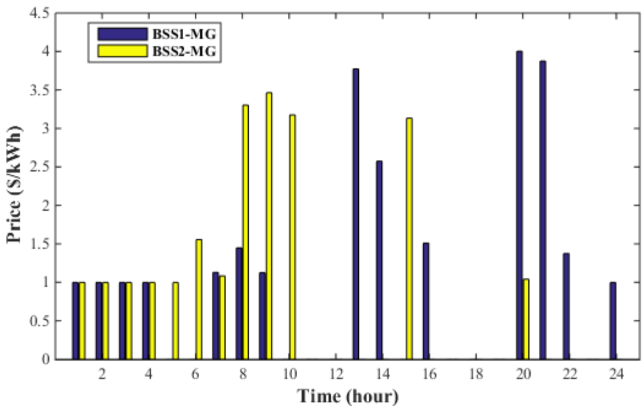

FIGURE 7. **Prices of the energy transaction plan when γ is one.**

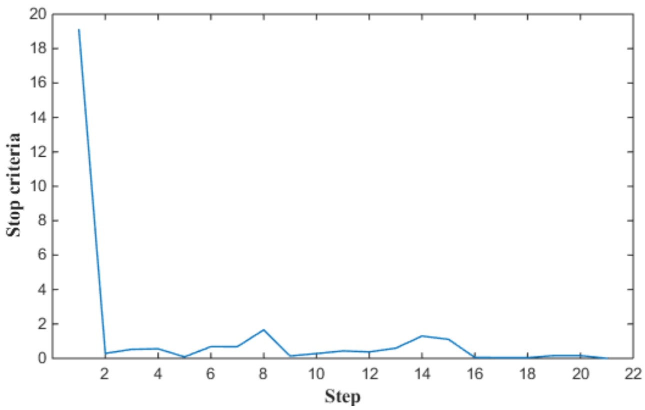

FIGURE 8. **Convergence of the iterative algorithm for the energy transaction plan when γ is one.**

TABLE II
THE PROFIT OF BSSS IN DIFFERENT CONDITIONS.

Description	Profit of BSSs ($)
$\gamma = 0$	10256.9
$\gamma = 0.01$	9992.8
$\gamma = 0.1$	8963.1
$\gamma = 1$	9209
Normal condition	5234

Case 2: It is obvious if each BSS cannot supply the swap demand of EV batteries, it cannot sell energy to MG during the emergency period. But in this case, it is assumed that the number of full batteries in each BSS is equal to the EVs batteries swap demand during the emergency period for that BSS. The other condition of this case is similar to Case 1. Therefore, BSSs cannot discharge the full batteries to sell energy to MG. The only way for BSSs to improve the resilience of MG during emergency period is to charge the empty batteries when MG has surplus energy and discharge them when MG needs importing energy to avoid load shedding. This is the concept of demand side management that BSSs can pay for MG and enhance the resilience of MG. Therefore, with the proposed efficient framework, MG resilience against islanding is improved without spending money to install extra energy storage. In other words, resilience of MG against islanding is enhanced with the potential of BSSs. Based on the bonus mechanism in the proposed efficient framework, this is also a winning game for BSSs that they can earn money in the resilience improvement of MG by charging the empty batteries with the market prices and discharging them with higher prices. To confirm the concept, the problem is solved only when $\gamma = 1$ and the energy transaction plan is depicted in Fig. 9. With this energy transaction plan, BSSs charge the empty batteries at hours 1-5 and discharges them at hours 8, 9, 13, 20 and 21. The result of this case shows the resilience of MG against islanding is improved by 9.1%.

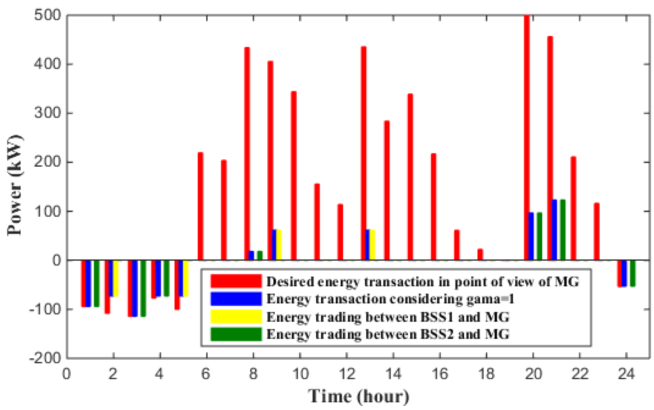

FIGURE 9. **Energy transaction plan when γ is one in Case 2**

VI. CONCLUSION

An efficient bi-level framework has been proposed to enhance the resilience of MG against islanding by BSSs. In this regard, for the upper-level problem, the cost of unsupplied loads of MG considering the value of lost loads during the emergency period was minimized and the desired energy transaction including surplus energy and unsupplied loads was reported to the BSSs coordinator. The lower-level problem was solved with an iterative algorithm by the BSSs coordinator to maximize the cost of energy trading with MG and the income of EVs battery swapping. Furthermore, a term was added to the objective function of the lower-level problem that causes different plans of energy transactions considering the reported desired energy transaction as a reference were obtained. A price mechanism based on a bonus was designed in the proposed framework that MG intended to sell surplus energy with market price and purchase energy with a variable bonus. The best plan of energy transaction was chosen by MG considering different parameters such as the behavior of loads besides the value of lost loads. The cyber link between MG and BSSs coordinator was only used once and twice by the BSSs coordinator and MG, respectively. A new formulation with fewer variables in comparison to the previous works was presented for the operation of BSS. To verify the effectiveness of the model, the proposed framework was run for an MG and two BSSs for two cases. In the first case, it is shown the proposed model is attractive for both MG and BSSs. MG can

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enhance resilience considering different parameters by receiving different plans of energy transactions that are offered based on the reported desired energy transaction. BSSs can earn more profit in comparison to the normal condition without jeopardizing their main responsibility. Furthermore, the second case was designed to show that with the proposed framework, BSSs can improve the resilience of MG against islanding even so they have no full battery. They can play this role by modifying the demand of MG during the emergency period with empty batteries.

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